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Coalition Formation in Multi-Agent Systems Based on Bottlenose Dolphin Alliances

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***Abstract*— Male bottlenose dolphins, *Tursiops truncatus*, found off the coast of Western Australia and Florida, often form varied levels of alliances to capture females and increase their chances of mating. One such alliance, known as the first-order alliance, consists of 2-3 dolphins that share a very strong "bond", formally known as the Association coefficient in behavioral biology. We formalize factors that affect the coefficient, and analyze their influence in building alliances in the context of multi-agent coalition formation. We produce a model of the first-order alliance as a hybrid automaton, based solely on local information evolving over spatially defined interaction topologies, where the model is expressive enough to capture the biological phenomenon, yet simple enough to derive results through analysis.**

I. INTRODUCTION

Coalition formation, viewed as a general principle in social systems, is an important cooperation method and has received a lot of attention, e.g., [1], [2], [3]. Agents form groups to achieve a goal, increase payoff, or utilize resources. Our goal is to develop a dolphin-inspired coalition formation algorithm in the context of multi-agent coordination.

Most research has focused on creating agent coalitions through primarily two methods, namely, using game theory and social reasoning, as seen in [4] and [5], respectively. In these approaches, there is usually some task that needs to be accomplished and research has focused on creating coalitions that maximize the resource utilization. Game theory is mainly used to compare the effectiveness of the formed coalitions, rather than providing an algorithm to create them [2]. The social reasoning based algorithms, such as those in [5] or [6], utilize the ability of an "intelligent agent" to maintain an external description - goals, actions, plans - of other agents and form coalitions accordingly. Some of these methods, e.g., [7], rely on the availability of central control, while decentralized algorithms, as seen in [8], are usually implemented in a task-oriented environment. Often "user agents" [9] or "auctioneers" [10] are used to advertise the request to create a coalition by other agents in the network and previous research, as seen in [11], has also focused on finding the optimal division of agents through search algorithms.

We chose the male bottlenose dolphins, *Tursiops truncatus*, as our inspiration for coalition formation, since they form complex alliances to cooperate and compete with one another to capture females. The objective is to find a mating partner, but males know that they cannot separate a female from its pod on their own; thus, they form alliances with other males and work together to capture a female and increase their chances of mating [23]. Since members within an alliance have to share the female, there is competition among males and as a result, three levels of alliances - first-order, second-order, and super-alliance - are dynamically formed, which is very interesting from a multi-agent coordination point of view.

The first-order alliance is usually made up of 2-3 dolphins that tend to share a strong bond; thus making such an alliance very stable. (The factors governing whether two dolphins will join in an alliance is discussed more in detail in the next section.) The goal of the first-order alliance is to capture a female swimming by itself or with other females in a pod [23]. The second-order alliance is formed by combining two first-order alliances and as a result, consists of 4-6 dolphins. The goal of the second-order alliance is to steal a female already being "herded" by another first-order alliance [12]. As a balance of nature, to ensure that second-order alliances do not always have monopoly over the females, super-alliances are sometimes formed. These are loose coalitions of 14-25 dolphins created to take on the two other stable, yet smaller, alliances [21].

We model the dolphins as first-order networks in which the agents make autonomous decisions based on local interactions with other agents. As such, we attempt to produce a model that is expressive enough to capture the underlying biological phenomena of bottlenose dolphin alliances; at the same time, we want our model to be as simple as possible so that it remains open to analysis.

The rest of the paper is organized as follows: Section II describes, in detail, the three levels of alliances formed by bottlenose dolphins. Section III formalizes factors that influence coalition formation and presents our model of the first-order alliance along with analysis results. Simulation results are provided in Section IV and Section V presents the conclusions.

II. BOTTLENOSE DOLPHINS

Cooperative behavior in social animals has often been the inspiration to many sub-problems in multi-agent robotics, as seen in [17], [18], [27] and bottlenose dolphins exhibit complex and social behaviors that are interesting from a networked control point of view.

Cetaceans, which include whales and dolphins, are very intelligent animals. Dolphins rate 2nd in the E.Q. list for

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animals weighing over 1kg, just behind humans [19] (the Encephalization Quotient (E.Q.) is the brain to mass ratio and a good indicator of intelligence). They have a well defined social hierarchy [19] and are smart enough to use marine sponges as foraging tools to avoid abrasions [22]. Dolphins live in fission-fusion societies, i.e., during the day, the main group can break up (fission) into smaller groups to play, explore, or even forage for food, but later, they may rejoin (fusion) the primary group to share food or participate in other activities [15]. In the presence of threats, they often use scouts to locate food [20] and once they locate fish, dolphins have interesting methods of actually catching their prey. In one of the methods, known as the horizontal carousal, the dolphins encircle the fish and slowly tighten these encirclements to constrict the movement of their prey. After the circle is small enough, the dolphins dive into the school of fish to feed, one at a time, while maintaining the integrity of the circle, as seen in [15], [27].

The cooperative behaviors that are displayed among dolphins include: advertising resources, foraging and capturing prey, defending other members, and searching for mates [16] by forming alliances [13]. The three levels of alliances are explained more in detail in the sub-sections that follow.

A. First-order Alliances

In this type of an alliance, a pair or a triplet of male dolphins capture a female and herd it by swimming in a very specific formation (in the case of a pair, the two males remain slightly behind and on either side of the female).

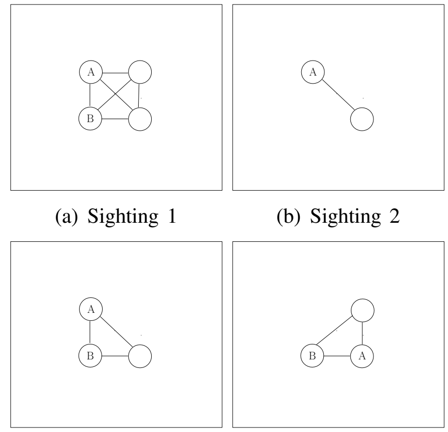
As mentioned before, male bottlenose dolphins form alliances to capture females, where the overriding objective is to find a mating partner. In [12], the researchers use the "Association coefficient" to identify whether two dolphins are in an alliance and the coefficient is given by

$$\text{Association coefficient} = \frac{100 \times 2N_t}{(N_a + N_b)}$$

where N_t is the total number of party sightings (a pod of dolphins within 10m of each other by the researchers [12]) in which dolphins A and B are seen together and N_a and N_b are the number of party sightings for A and B, respectively. Thus the Association coefficient is an indicator of the degree of cooperation between male dolphins. The coefficient ranges from 0, i.e., two dolphins are never sighted together, to 100 which indicates that two dolphins are seen everywhere together. Figure 1 can help us further illustrate this concept, where $N_t = 3$, $N_a = 4$, $N_b = 3$. The Association coefficient in this case is 85.7, which is typical for male dolphins in a first-order alliance. This is in the same coefficient range as those found between females and their nursing calves and since the calves hardly ever leave the mother's sight during nursing, this coefficient indicates that a strong bond exists between males in a first-order alliance.

B. Second-order Alliances

To understand a second-order alliance, let us consider three first-order alliances: A, B, and C, as shown in Figure



(a) Sighting 1 (b) Sighting 2

(c) Sighting 3 (d) Sighting 4

Fig. 1. Four sightings of dolphins A and B. Notice that the two dolphins are seen together in three out of the four sightings.

2. As seen in [12], it is often the case that a first-order alliance realizes that it cannot steal the female it wants from another first-order alliance of the same size since the outcome of a fight is unpredictable. Alliance B realizes that to steal the female from Alliance C, it is more favorable to recruit another first-order alliance, which is Alliance A in our example. After the capture, only one of the two alliances ends up herding the female. Alliances between alliances often shift and such multiple levels of male alliances, with both hostile and favorable interactions, appear only in dolphins and humans [12].

C. Super-alliance

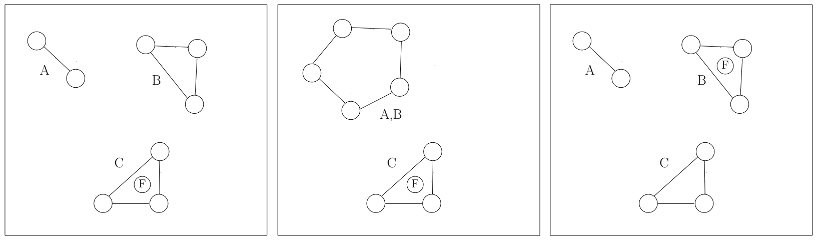
The super-alliance, as described in [21], is made up of 14-25 members and is very volatile, with a mean Association coefficient of 58 among its members. This level of alliance possesses a direct threat to the smaller yet stable alliances (maximum of 3 members in a first-order and 6 members found in second-order alliance, with Association coefficients between $80-90$ in both).

Our attempt to model the underlying biological phenomena of alliance forming in bottlenose dolphins is the topic of our next section. We model the first-order alliance only, since it is the simplest level of alliance available to develop a dolphin-inspired coalition formation algorithm for multi-agent systems. This effort can be viewed as first-step towards modeling the complex cooperative/competitive relation that exists between dolphins and applying it to multi-agent systems.

III. FIRST-ORDER ALLIANCE MODEL

A. Network topology

Our network will consist of N male dolphins with the corresponding index sets $\mathbf{N} = \{1, \ldots, N\}$. Also, the dolphin states will evolve in a three-dimensional space, i.e., $x_i \in \mathbb{R}^3$, $\forall\, i \in \mathbf{N}$. To produce a simple, yet sufficiently expressive model of the dolphin alliance, we need to discuss their



(a) First-order alliance C is herding a female.
(b) Alliances A and B form a second-order alliance.
(c) Alliances A and B take turns to herd the female.

Fig. 2. A second-order steal.

communication methods in detail. Dolphins are primarily audial creatures and perceive their environment through their echolocation system, which involves utilizing both sonar and monitoring echoes formed from producing rapid clicks [14], [15]. This results in a limited interaction range over which dolphins can communicate with each other, and thus, we can define an edge set $\mathbf{E}(t)$ as $(i,j) \in \mathbf{E}(t) \Leftrightarrow \|x_i(t) - x_j(t)\| \leq \Delta$, which implies that two dolphins, i and j, are "neighbors" and form an edge, or in other words, they can communicate if they are within a distance Δ of each other. The set $\mathbf{N}(i)$ will be used to denote the set of neighbors of agent i. This construction ensures that the resulting Δ-disk proximity graph, $\mathbf{G}(t) = \mathbf{N} \times \mathbf{E}(t)$, is simple (no self-loops) and undirected, as seen in [24], [25]. Our assertion of the nearest-neighbor rule, where an agent can only communicate with its neighbors, for inter-agent interactions is further corroborated by [16], which documents that each dolphin moves with a "bubble" around it, which other dolphins do not intrude, and is aware of the position of its neighbors.

We are now ready to present a coalition formation algorithm inspired by bottlenose dolphins in the context of multi-agent coordination.

B. Coalition Formation

The Association coefficient described in Section II is a good measure of the camaraderie between dolphins and this will be the key determinant in our modeling of alliances. We let the **Association coefficient**, $\alpha_{i,j}(t)$, be the companionship that agent i exhibits towards agent j. This relation is not necessarily symmetric, i.e., $\alpha_{i,j}(t) \neq \alpha_{j,i}(t)$. Since the Association coefficient for the members in a first-order alliance is usually > 85, we can borrow this notion and arrive at a necessary condition for creating an alliance. Thus, the necessary condition for agent i and j to form an alliances is that both $\alpha_{i,j}(t)$ and $\alpha_{j,i}(t)$ have to exceed a specified threshold, denoted by $\alpha^\star$.

Our conversations with Lori Marino, a Psychobiologist at Emory University, revealed a number of factors that are thought to influence the Association coefficient. She postulates that familiarity between dolphins might increase their cooperation, while rejection of forming an alliance might increase the animosity between them. Dolphins aside, our goal is to develop a coalition formation algorithm for a multi-agent system, but based on the conversation, we introduce two new coefficients - **Rejection coefficient**, $\rho_{i,j}(t)$, and **Familiarity coefficient**, $\phi_{i,j}(t)$ - and allow them to affect the Association coefficient between agents as follows:

$$\alpha_{i,j}(t) = \phi_{i,j}(t) - \rho_{i,j}(t)$$

where $\rho_{i,j}(t)$, is a measure of the rejection experienced by agent i from agent j, when a request from agent i to form an alliance is denied by agent j, and $\phi_{i,j}(t)$ measures the familiarity that develops between agent i and agent j. We want our model to capture the biological phenomenon of dolphin alliances, but at the same time, we need it to be as simple as possible so that it is open to analysis. This motivates our choice for a bounded Association coefficient and first-order differential equations as the dynamics for the Rejection and Familiarity coefficient. Thus, the Rejection coefficient evolves according to

$$\dot{\rho}_{i,j}(t) = \begin{cases} \rho_{max} - \rho_{i,j}(t) & \text{if } j \text{ rejects } i \\ 0 & \text{otherwise} \end{cases}$$

where $\rho_{max} > \rho_{i,j}(0) \geq 0$. And the Familiarity coefficient has the following dynamics:

$$\dot{\phi}_{i,j}(t) = \begin{cases} \phi_{max} - \phi_{i,j}(t) & \text{if } a_{i,j} = 1 \\ 0 & \text{otherwise} \end{cases}$$

where $\phi_{max} > \phi_{i,j}(0) \geq 0$ and $a_{i,j}$ is the nondiagonal entry of the Adjacency matrix. If we assert that $\alpha_{i,j}(t) \geq 0 \ \forall\ t$, then we have the constraint: $\phi_{i,j}(0) \geq \rho_{i,j}(0)$.

To form a coalition, we propose a model in which each agent first identifies, amongst its neighbors, up to two agents with which it shares the highest Association coefficients, beyond the threshold $\alpha^\star$. Thus, for agent i, we can define a set $\mathbf{C}^1(i)$ that contains the agent with the greatest Association coefficient towards agent i as

$$\mathbf{C}^1(i) = \{j \mid \alpha_{i,j} > \alpha_{i,m},\ \alpha_{i,j} \geq \alpha^\star\ \forall m \in \mathbf{N}(i) \setminus \{j\}\}$$

and define the set $\mathbf{C}^2(i)$ that contains the agent with the second-greatest Association coefficient towards agent i as

$$\mathbf{C}^2(i) = \{k \mid \alpha_{i,k} > \alpha_{i,m},\ \alpha_{i,k} \geq \alpha^\star\ \forall m \in \mathbf{N}(i) \setminus (\{k\} \cup \mathbf{C}^1(i))\}.$$

Thus, for agent i, the two candidates for building an alliance are contained in the **Candidate set** $\mathbf{C}(i) = \mathbf{C}^1(i) \cup \mathbf{C}^2(i)$.

Since the first-order alliance can only contain a maximum of three dolphins, we have $|\mathbf{C}(i)| = \{0,1,2\}\ \forall i \in \mathbf{N}$, where $|\cdot|$ represents cardinality.

The Candidate set only contains potential alliance members and to identify the agents that make the transformation from candidate to partner, we define the **Alliance coefficient**, $q_{i,m}$, given by

$$q_{i,m} = \begin{cases} 1 & \text{if } m \in \mathbf{C}(i) \\ 0 & \text{otherwise} \end{cases} \quad \forall m \in \mathbf{N}(i)$$

Thus, agent i and m form an alliance if and only if $q_{i,m} = 1$ and $q_{m,i} = 1$ and agent i is rejected by agent m if and only if $q_{i,m} > q_{m,i}$. Agents i and j form a first-order pair if either of the following conditions hold:

1) $|\mathbf{C}(i)| = 1$ and $q_{j,1} = 1$
2) $|\mathbf{C}(i)| = 2$ and $q_{j,i} > q_{k,i}$

where $j \in \mathbf{C}(i)$ and $k \in \mathbf{C}(i) \setminus \{j\}$. And, agents i, j, and k form a triplet if the following conditions hold:

1) $|\mathbf{C}(i)| = 2$
2) $q_{j,1} = 1$ and $q_{k,1} = 1$
3) $q_{j,k} = 1$ and $q_{k,j} = 1$

Thus, in the case of a triplet, each agent must be in the candidate set of the other two.

State	Dynamics	Reset Condition
$\lvert\mathbf{C}(i)\rvert = \varnothing$	$\dot{\phi}_{i,j} = a_{i,j}(\phi_{max} - \phi_{i,j})$ $\dot{\rho}_{i,j} = 0$	$\phi_{i,j}(t) := \phi_{i,j}(0)$ $\rho_{i,j}(t) := \rho_{i,j}(0)$
1.a	$\dot{\phi}_{i,j} = a_{i,j}(\phi_{max} - \phi_{i,j})$ $\dot{\rho}_{i,j} = 0\ \forall\ j \in \mathbf{N}(i)$	$\rho_{i,arg(\mathbf{C}^1(i))}(t) := \rho_{i,arg(\mathbf{C}^1(i))}(0)$
1.r	$\dot{\phi}_{i,j} = a_{i,j}(\phi_{max} - \phi_{i,j})$ $\dot{\rho}_{i,j} = 0\ \forall\ j \in \mathbf{N}(i) \setminus \mathbf{C}^1(i)$ $\dot{\rho}_{i,arg(\mathbf{C}^1(i))} = \rho_{max} - \rho_{i,arg(\mathbf{C}^1(i))}$	
2.aa	$\dot{\phi}_{i,j} = a_{i,j}(\phi_{max} - \phi_{i,j})$ $\dot{\rho}_{i,j} = 0\ \forall\ j \in \mathbf{N}(i)$	$\rho_{i,j}(t) := \rho_{i,j}(0)\ \forall\ j \in \mathbf{C}(i)$
2.ar	$\dot{\phi}_{i,j} = a_{i,j}(\phi_{max} - \phi_{i,j})$ $\dot{\rho}_{i,arg(\mathbf{C}^1(i))} = 0$ $\rho_{i,arg(\mathbf{C}^2(i))} = \rho_{max} - \rho_{i,arg(\mathbf{C}^2(i))}$ $\dot{\rho}_{i,j} = 0\ \forall\ j \in \mathbf{N}(i) \setminus \mathbf{C}(i)$	$\rho_{i,arg(\mathbf{C}^1(i))}(t) := \rho_{i,arg(\mathbf{C}^1(i))}(0)$
2.ra	$\dot{\phi}_{i,j} = a_{i,j}(\phi_{max} - \phi_{i,j})$ $\rho_{i,arg(\mathbf{C}^1(i))} = \rho_{max} - \rho_{i,arg(\mathbf{C}^1(i))}$ $\dot{\rho}_{i,arg(\mathbf{C}^2(i))} = 0$ $\dot{\rho}_{i,j} = 0\ \forall\ j \in \mathbf{N}(i) \setminus \mathbf{C}(i)$	$\rho_{i,arg(\mathbf{C}^2(i))}(t) := \rho_{i,arg(\mathbf{C}^2(i))}(0)$
2.rr	$\dot{\phi}_{i,j} = a_{i,j}(\phi_{max} - \phi_{i,j})$ $\rho_{i,arg(\mathbf{C}^1(i))} = \rho_{max} - \rho_{i,arg(\mathbf{C}^1(i))}$ $\rho_{i,arg(\mathbf{C}^2(i))} = \rho_{max} - \rho_{i,arg(\mathbf{C}^2(i))}$ $\dot{\rho}_{i,j} = 0\ \forall\ j \in \mathbf{N}(i) \setminus \mathbf{C}(i)$	

TABLE I

DYNAMICS AND RESET CONDITION OF THE HYBRID AUTOMATA.

Event Set	Extentional Definition
$\lvert\mathbf{C}(\mathbf{i})\rvert = \varnothing$	$\{\}$
1.a	$\{q_{arg(\mathbf{C}^1),i} = 1\}$
1.r	$\{q_{arg(\mathbf{C}^1),i} = 0\}$
2.aa	$\{q_{arg(\mathbf{C}^1),i} = 1,\ q_{arg(\mathbf{C}^2),i} = 1\}$
2.ar	$\{q_{arg(\mathbf{C}^1),i} = 1,\ q_{arg(\mathbf{C}^2),i} = 0\}$
2.ra	$\{q_{arg(\mathbf{C}^1),i} = 0,\ q_{arg(\mathbf{C}^2),i} = 1\}$
2.rr	$\{q_{arg(\mathbf{C}^1),i} = 0,\ q_{arg(\mathbf{C}^2),i} = 0\}$

TABLE II

EXTENTIONAL DEFINITION OF THE EVENT SETS OF THE HYBRID AUTOMATA. EACH ELEMENT IN THE SET REPRESENTS AN EVENT.

C. Hybrid Automaton Representation

A hybrid automaton is used to model a dynamic system with both continuous and discrete variables, as seen in [26]. Since agents might enter or leave each others Candidate sets, the system dynamics will undergo discrete transitions. Hence, we model the first-order alliance as a hybrid automaton, where the continuous dynamics ($\phi_{i,j}(t)$ and $\rho_{i,j}(t)$) unfold within the discrete states. Tables I and II are used to decode the hybrid automata used to model the first-order alliance in Figure 3.

The dynamics of each state and the reset condition of the automaton when entering that state is described in Table I. The state names use the convention `Number Of Candidates.Status Of Request` to name the states in the automaton. For agent i, `Number Of Candidates`$=|\mathbf{C}(i)|$. If $|\mathbf{C}(i)| = 1$, `Status Of Request`$\in \{a,r\}$ and if $|\mathbf{C}(i)| = 2$, then `Status Of Request`$\in \{aa,ar,ra,rr\}$, where "a" and "r" represent accept and reject, respectively. Thus, state $2.ar$ indicates that agent i has two candidates, $arg(\mathbf{C}^1(i))$ and $arg(\mathbf{C}^2(i))$, for forming an alliance and they accept and reject the offer, respectively.

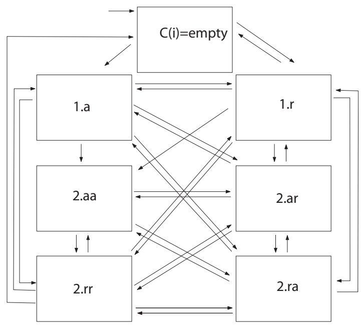
The name of a state also represents the set of events that triggers the transition from all other states to that state; it is displayed in bold to indicate it is a set, as shown in Table II.

The hybrid automaton model for agent i, HA_i is shown in Figure 3(a). The hybrid automaton for a multi-agent system with N agents is a parallel composition of the automaton of the individual agents, i.e., $HA = HA_1 \parallel HA_2 \parallel \ldots \parallel HA_N$.

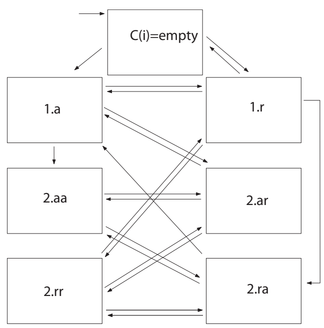
Since our automaton is event-driven, we have two possibilities regarding state transitions, namely, synchronized and asynchronized transitions. In the case of a synchronized transition, there is a chance of multiple events occurring simultaneously. To determine the number of transitions needed to go from state A to state B, we simply look up the event set $\mathbf{A} \cap \mathbf{B}$ from Table II; and if $\mathbf{A} \cap \mathbf{B} \neq \varnothing$, then only one event is required; but if $\mathbf{A} \cap \mathbf{B} = \varnothing$, then two events are required. For example, a transition from state $2.aa$ to $2.rr$ is possible in a synchronous model, as shown in Figure 3(a), although it requires two events to fire simultaneously since $\mathbf{2.aa} \cap \mathbf{2.rr} = \varnothing$. However, for anysnchronized transitions, we assume that the probability of the multiple events firing at the same time is 0. The transition from state $2.aa$ to state $2.rr$ would no longer be possible, as shown in Figure 3(b). The following results are based on the analysis of the hybrid automaton representation derived in the previous sub-section.

D. Analysis Results

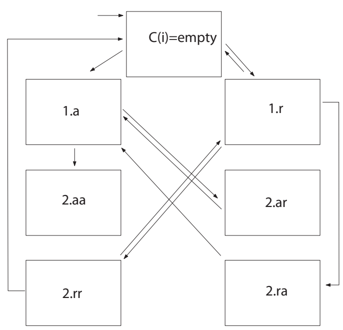
We will assume that the Candidate set is updated sequentially, i.e., it is first populated by $\mathbf{C}^1$, followed by $\mathbf{C}^2$. Hence, a triplet can form only by adding an agent to an existing pair.



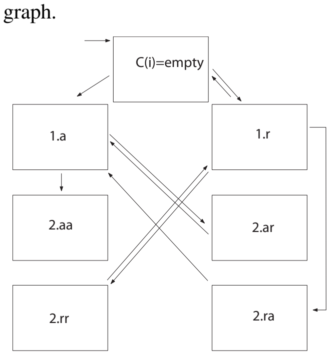
(a) Synchronous, dynamic interaction graph.



(b) Asynchronous, dynamic interaction graph.



(c) Synchronous, static interaction graph.



(d) Asynchronous, static interaction graph.

Fig. 3. First-Order alliance hybrid automata model of agent i.

Lemma 3.1: State $\mathbf{C}(i) = \varnothing$ can never be reached from the state $1.a$ in a single transition.

Proof. State $1.a$ implies that $|\mathbf{C}(i)| = 1$, $\mathbf{C}^1(i) = \{j \mid \alpha_{i,j}(t) > \alpha_{i,m}(t),\ \ \alpha_{i,j}(t) \geq \alpha^\star \ \ \forall m \in \mathbf{N}(i) \setminus \{j\}\}$ and $q_{arg(\mathbf{C}(i)),i} = 1$. Thus, $\phi_{i,arg(\mathbf{C}(i))}(t)$ monotonically increases while $\rho_{i,arg(\mathbf{C}(i))}(t) = 0$; as a result, $\alpha_{i,arg(\mathbf{C}(i))}(t)$ monotonically increases and remains the greatest Association coefficient displayed towards agent i from amongst its neighbors. $\mathbf{N}(arg(\mathbf{C}(i)))$ does not affect $|\mathbf{C}(i)|$ and changes in $\mathbf{N}(i)$ leads to two possibilities: $|\mathbf{C}(i)|$ may increase or remain unaffected. Hence, $|\mathbf{C}(i)|$ cannot decrease in a single transition from state $1.a$. □

Lemma 3.2: States $1.a$ and $1.r$ can never be reached from the state $2.aa$ in a single transition.

Proof. State $2.aa$ implies that, $\forall j \in \mathbf{C}(i)$, $|\mathbf{C}(i)| = 2$, $\alpha_{i,j}(t) > \alpha^\star$ are the two greatest Association coefficients towards agent i from amongst its neighbors, and $q_{j,i} = 1$. $\phi_{i,j}(t)$ monotonically increase, $\rho_{i,j}(t) = 0$ and hence, $\alpha_{i,j}(t)$ monotonically increase. At this point, changes in either $\mathbf{N}(arg(\mathbf{C}^1(i))$, $\mathbf{N}(arg(\mathbf{C}^2(i))$, or $\mathbf{N}(i)$ do not affect $|\mathbf{C}(i)|$. Hence, $|\mathbf{C}(i)|$ cannot decrease in a single transition. □

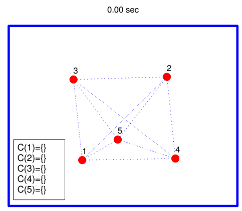
We notice that, the cardinality of the Candidate set does not decrease, in a single transition, from a state where at least one request for an alliance is accepted.

Theorem 3.1: For a static interaction graph, a first-order alliance (pair or triplet) can never lose alliance members.

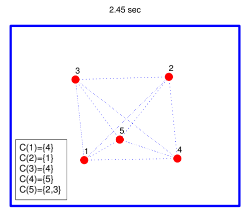
Proof. Agent i is in a first-order pair if it is in either state $1.a$, $2.ar$ or $2.ra$. From state $1.a$, since $\mathbf{E}(t)$ is static, $\alpha_{i,arg(\mathbf{C}^1(i))}(t)$ monotonically increases and remains the greatest Association coefficient towards agent i and as a result, a first-order pair in a static graph can never lose alliance members. $\mathbf{C}(i)$ updates sequentially, so if $\mathbf{C}^2(i) \neq \varnothing$, and $q_{arg(\mathbf{C}^2(i)),i} = 0$, the state transitions to $2.ar$, where $\alpha_{i,arg(\mathbf{C}^2(i))}(t)$ monotonically decreases and only transitions back to $1.a$ when $|\mathbf{C}(i)| = 1$. Similarly, from state $2.ra$, $\alpha_{i,arg(\mathbf{C}^1(i))}(t)$ monotonically decreases only transitions to $1.a$ if $|\mathbf{C}(i)| = 1$. From state $1.a$, if $q_{arg(\mathbf{C}^2(i)),i} = 1$, the state transitions to $2.aa$, where, according to Lemma 3.2 under a static edge set $\mathbf{E}(t)$, $\alpha_{i,j}(t)$ monotonically increase $\forall j \in \mathbf{C}(i)$ and remain the two greatest coefficients exhibited towards agent i. Hence, for a static graph, a first-order triplet never loses alliance members. □

Corollary 3.1: For a static interaction graph, the size of the coalition can only get larger.

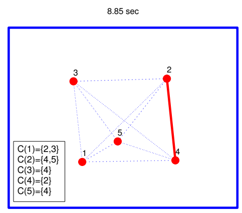
These results explain the deadlock in state $2.aa$ of Figures 3(c)-(d).



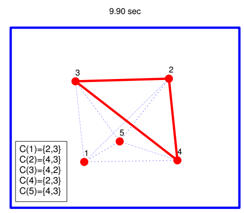
(a) The Candidate sets are empty.



(b) The Candidate sets are populated.



(c) Agents 2 and 4 form a pair.



(d) Agents 2, 3, and 4 form a triplet.

Fig. 4. Coalition formation inspired by bottlenose dolphins. The dotted lines denote edges between agents and the solid line denotes an alliance.

IV. SIMULATION

To illustrate the fact that a coalition size can only get larger in a static graph, we simulate our dolphin-inspired algorithm with 5 agents. From Figure 4, it is clear that for a static graph, a pair or triplet does not lose alliance members.

V. CONCLUSIONS

Male bottlenose dolphins, *Tursiops truncatus*, often form varied levels of alliances to capture females and increase their chances of mating. We model the dolphins as first-order networks where agent interactions are defined through a proximity graph. Our goal was to produce a model that is rich enough to capture this complex biological phenomenon, but at the same time, is as simple as possible for us to develop a dolphin-inspired coalition formation algorithm in the context of multi-agent coordination.

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